SNOW ON FOREST SLOPES

By

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Introduction

Everyone, from the water company hydrographer to the ski tow operator, wants to know where the snow lies deepest and how long it will last. But every place is different, so we measure snow here and infer what must be over there. Our inference is as good as our knowledge of what makes for differences in snow accumulation and melt.

Some results of a study aimed at helping make these inferences are presented in this paper. It is a prelude to rather intensive studies of snow in California and, particularly, of how snow accumulation and melt can be managed for the improvement of water yield. Available for study were the snow-course data collected by the Cooperative Snow Investigations at the Central Sierra Snow Laboratory (CSSL). The question was, what clues to variations in snow accumulation and early spring melt on different slopes and under different forest conditions could be obtained from further analysis of these data?

Methods

The approach was statistical. We determined the relation of both the snow accumulation and the rate of melt to terrain and forest characteristics at CSSL snow courses by means of multiple regression analysis. We then used analysis of variance to test the significance of explained variance of groups of terrain and forest variables.

Multiple regression was adopted to evaluate the separate effects of various terrain and forest conditions. The method gives a measure of the amount of variation in snow and melt associated with each variable, the statistical significance of the effect, and the accuracy of the prediction of the combined effects of all of the variables. The success of the method depends largely on how well we can select the variables and data for analysis.

Selection of Snow Courses

One might think, offhand, that the more snow courses the better, but this is not necessarily true. Since we are analyzing for the effects that differences in snow course locations and characteristics have on the snowpack, the more different the courses are, the better the analysis. We want snow courses with every combination of high and low values of steepness, exposure, forest cover, or other characteristics to be evaluated. Ideally, the courses should be different in the characteristics to be analyzed and similar in other respects.

A table similar to Table 1 was prepared, showing the forest shade at all available snow courses, grouped according to elevations, slopes, and aspects. The purpose was to see how good a distribution of terrain and forest differences could be obtained. Ideally, we should have an equal number of courses for each slope, elevation, and aspect, and forest shade should differ widely among the courses. Such a table, drawn up before new courses are established, would aid considerably in the selection of appropriate courses. But with an unequal distribution of conditions, we can only try to balance the data by disregarding courses which contribute no significant differences.

Thirty-two snow courses were selected for analysis (Table 1). These had the greatest differences in elevation, slopes, and forest conditions, and had snow accumulation and melt data measured at nearly the same dates. The distribution in Table 1 is deficient in snow courses with low-elevation steep slopes and also forested high-elevation slopes having aspects other than south. With these exceptions, the courses available for analysis can be considered fairly well balanced in forest and terrain variables.

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Table 2.-- Regression results, effects of terrain and forest upon snowpack accumulation and melt, Central Sierra Snow Laboratory, April, 1951

EFFECT ON APRIL 10, 1951, SNOWPACK ACCUMULATION [1]

Item	Terrain variables[2]						Forest variables[2]				Regression equation constant	Explained variance
	El	C	Ex	En	S	As	Sh	Sh2	Ws	Fs		
Units	100 ft	----	10°	ly/day	Pct	°S	Pct	$\frac{Pct^2}{100}$	----	----		
Range (limits)	68-86	1-5	3-26	150-440	0-40	0-170	0-90	0-81	1-11	2-5		
Range (total)	(18)	(4)	(23)	(290)	(40)	(170)	(90)	(81)	(10)	(3)		
	Gain or loss in inches										Inches	Pct
Analysis 1	38.8	-5.6	-3.9	-20.8	--	--	[3] -1.0	[3] -7.7	3.6	-14.8	-84.1	62
Analysis 2	42.8	-7.2	-10.2	--	-7.2	14.5	[3] -1.0	[3] 4.4	1.5	-13.4	-119.0	54
Analysis 3	34.2	-4.3	-10.8	-14.9	--	--	--	--	--	--	-85.4	50
EFFECT ON APRIL 10-20, 1951, MELT RATE [1]												
	Increase or decrease in inches per degree-day										Inches	Pct
Analysis 4	.035	.024	.052	.060	--	--	[4] .068	[4] -.044	-.003	-.061	-0.114	65
Analysis 5	-.011	.018	.026	.079	--	--	--	--	--	--	0.038	52

[1] "Effects" are the change in snowpack water equivalent (Analyses 1,2,3) or melt rate (Analyses 4,5) associated with a change in each variable equal to its entire range, other variables being held constant. Thus, as elevation increases from 68-86 (6800' - 8600'), the snowpack gains 38.8 inches. Original regression coefficients can be derived by dividing each "effect" by the total range in the variable.

[2] For definitions of variables, see text.

[3] Shw: winter shade, average sun declination of -15°41'.

[4] Sha: shade from April 10-20.

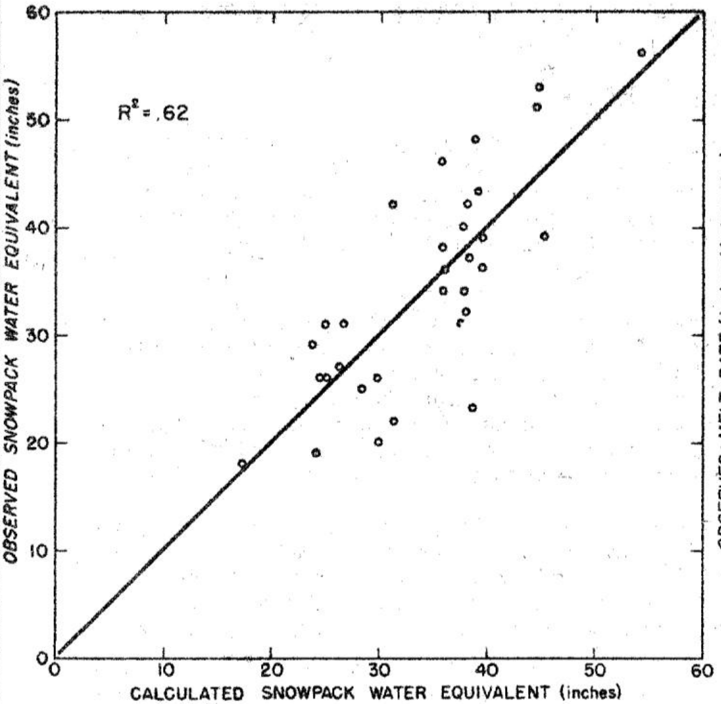

Figure 1.-- Observed vs. calculated snowpack at snow courses, Central Sierra Snow Laboratory, April 10, 1951 (Analysis 1, Table 2)

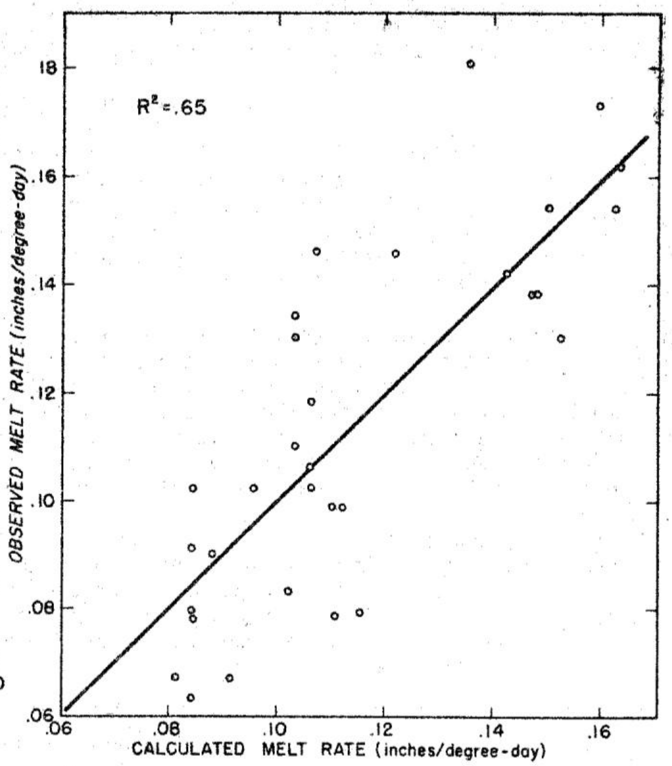

Figure 2.-- Observed vs. calculated melt rates at snow courses, Central Sierra Snow Laboratory, April 10-20, 1951 (Analysis 4, Table 2)

Selection of Variables

Two considerations governed the selection of variables. First, we felt that each terrain or forest factor expected to exert considerable influence on snow accumulation or melt must be indexed by a variable, for the influence of a neglected factor is hidden in the variables that are used and distorts their effects. Secondly, such index variables should be relatively easy to determine for each snow course.

Snow variables (the dependent variables in these analyses) were:

Sn - the April 10, 1951, snowpack water equivalent in inches, which indexed the snow accumulation near the time of maximum for that year, and

Ab - the April 10-20, 1951, ablation, or depth of decrease in snowpack water equivalent, in inches per degree-day above 35°F (temperature measured at CSSL headquarters), which indexed the early spring melt.

Since the accumulated snow was not always measured on exactly April 10 or April 20, some snow-course data had to be adjusted. The degree-day melt factor was determined for each course, using the snowpack water equivalent measurements and associated temperatures between snow survey dates. The degree-day factor was used to adjust snow measurements on dates varying from April 9-13 to an estimated April 10 water equivalent. The melt rates did not require adjustment, the melt factor being used as the April 10-20 melt rate.

Terrain and forest characteristics at each of the snow courses were the independent variables.

Terrain characteristics were:

El - elevation of snow course (hundreds of feet above MSL);

C - curvature, or shape of terrain at the snow course area (classified as: 1) highly concave, at bottom of slope, 2) moderately concave, 3) neutral, in mid-slope or level, 4) moderately convex, and 5) highly convex, at ridge);

Ex - exposure sector: that sector of a circle of 1/2 mile radius, centered on the snow course, within which there is no elevation higher than the snow course (azimuth limits of sector to nearest 10 degrees);

En - solar energy: the average shortwave radiation received on the snow course during the snow accumulation period October through March (langleys per day);

S - slope of snow course (percent); and

As - aspect: orientation of slope (to nearest 10 degrees azimuth from south).

Forest characteristics were:

Sh - shading of snow course by trees (percent of total possible sunshine; Shw - shading during winter (average sun declination of -15°41'); Sha - shading from April 10-20;

Ws - shelter from wind by trees immediately adjacent to south, from open to dense shelter (1-11); and

Fs - shelter from wind by trees up to 1/4 mile to south, from dense to open (1-5).

Thus, six terrain variables and three forest variables were used in the analyses.

Terrain variables at each snow course were determined from detailed topographic maps of each course or from measurements at the site. (1) The solar energy (En) was determined from the slope and aspect at each site, using tables of solar intensity prepared by the Fire Research Division of this Station. The energy amounts were corrected for the interception caused by nearby mountains and converted to units of langleys per day.[2] Forest shade was determined from aerial photographs by estimating the tree heights and distances of the snow-course points from the trees and applying the weights of solar energy in each azimuth quadrant. (2) Shielding from the wind (Ws) was also estimated from aerial photos. The vicinity cover (Fs) was determined from the forest Timber Stand map. (3)

ANALYSIS

The linear multiple regression analyses relating April 10 snowpack water equivalent and the April 10-20 melt rate to terrain and forest variables were done by electronic computer with punched IBM cards in less than one day, at a cost of $425. This same job would have taken weeks had it been done by a statistical clerk. The computer solved the simultaneous equations and computed the residuals (the difference between the observed and predicted values of the dependent variable). These residuals were then plotted against each of the independent variables to test for curvelinearity, and against the predicted values of the dependent variable to test the nature of the variance. These tests showed no detectable deviation from linearity; the variance was about the same for all predicted values of the dependent variable. Thus, the results may be considered useful indexes of the effects of terrain and forest and of the predictability of snow accumulation and melt.

REGRESSION RESULTS

Snow Accumulation Analysis

The regression analysis results are summarized in Table 2, which gives the actual range in each of the terrain and forest variables, the gain or loss in snowpack to be associated with a change in the variable over its entire range, and the amount of observed snowpack change explained by all of the variables acting together. Results show that elevation (El), solar energy (En), and forest variables (mostly Sh and Fs), in that order, caused the greatest differences in snowpack water equivalent (Analysis 1, Table 2). All the variables taken together explained about 62 percent of the snowpack variation between courses. A comparison of measured vs. calculated water equivalent on April 10 is shown in Figure 1. A second regression analysis (Analysis 2, Table 2) substituted separate slope and aspect variables in place of the solar energy variable. The explained variance was only 54 percent, showing that these two terrain variables were 15 percent less effective in explaining the total snowpack variance than was the energy variable. To obtain an indication of the effectiveness of the forest variables taken as a group, a third analysis was made, excluding them (Analysis 3, Table 2). Results showed that these forest variables explained about 24 percent more of the variation than was explained without them.

Melt Rate Analysis

The differences in April 10-20 snowpack ablation associated with differences in terrain and forest are also shown in Table 2. The solar energy received (En), the exposure of the course (Ex), and the density of the forest within 1/4 mile to the south (Fs), in that order, were the most important tested variables in increasing melt in mid-April (Analysis 4, Table 2). All the variables taken together explained about 65 percent of the melt rate variation between courses. A comparison of actual melt rates at the snow courses with calculated rates is shown in Figure 2. The effectiveness of the forest variables acting together on the melt rate was tested by excluding them (Analysis 5, Table 2); the results showed that the forest variables explained about 25 percent more of the variation in snowmelt than was explained without them.

DISCUSSION

What do the analyses suggest on how to improve our estimation of differences in snow accumulation and melt associated with differences in terrain and forest? We saw that putting the slope and aspect variables into the more direct form of the solar energy received on the slopes increased the explained variation in snowpack water equivalent. More improvement can be anticipated when we learn how to express more of the environmental variables in such terms. We hope to state forest variations in terms of the heat balance rather than the present empirical variables of shade and shielding from wind. To be able to do this, we are starting studies of snow physics and forest-snow hydrology in the Sierras.

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[2] Average incoming shortwave radiation on a horizontal surface for the period Oct. 1, 1950, to Mar. 31, 1951, at CSSL headquarters was 283 ly per day. (Average for February, 1951, was 282 ly.) Total sin θ for the seven hour angles $0^\circ - 180^\circ$ on a horizontal surface for an average winter declination of $-15^\circ 41'$ was 3.68. Solar energy in langleys for slopes other than horizontal was obtained by taking the sum of sin θ for that slope (and aspect) divided by 3.68 and times 283 langleys.

SUMMARY

The relation of snowpack water equivalent and melt at 32 snow courses at the Central Sierra Snow Laboratory to six terrain and three forest variables was determined by multiple regression analysis. Approximately 62 percent of the between-course variation in accumulated snow on April 10, 1951, and approximately 64 percent of the melt between April 10 and April 20, 1951, could be explained by the variables selected. A new variable, the solar energy received on different slopes, was found to explain about 15 percent more of the variation in snowpack than did the terrain variables of slope and aspect.

Snow accumulation increased with elevation about 2 inches per 100 feet, and decreased by 21 inches over the range of 150-440 langleys per day of incoming shortwave radiation received on various slopes. Inclusion of three forest variables added 24 percent to the explained variation among snow courses. Snow accumulation was decreased as much as 9 inches by the presence of trees near and over the snow course and was increased as much as 15 inches by trees to the south of the course.

Melt rate increased with the energy received, the degree of exposure of the course, and the density of the forest to the south. Inclusion of forest variables added 25 percent to the explained variation in melt rate among courses. Melt rate tended to increase with small amounts of forest shade and then decrease with larger amounts of shade.

The need for expressing all environmental variables in more direct physical terms is emphasized.

LITERATURE CITED

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(2) ANDERSON, H. W., "Forest-cover effects on snowpack accumulation and melt, Central Sierra Snow Laboratory," *Trans. Amer. Geophys. Union*, 37, pp. 307-312, 1956.
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Table 1.— Physiographic and forest shade characteristics of selected snow courses, Central Sierra Snow Laboratory, California

Elevation and slope	Forest shade when aspect of snow course was—			Total Number of Courses
	NW-NE	NE-SE or NW-SW	SW-SE	
	Pct	Pct	Pct	
Under 7,400 ft.				
0-12 pct	25	70, 75	15, 81	5
13-32 pct	20, 20, 20	72, 90	50, 25	7
33-50 pct	—	—	—	0
7,400 ft - 7,750 ft				
0-12 pct	—	10, 15, 30	12	4
13-32 pct	35	3, 20, 90	35, 42	6
33-50 pct	30, 30, 30	60	10	5
Over 7,750 ft				
0-12 pct	—	0	—	1
13-32 pct	—	—	50, 45, 5	3
33-50 pct	—	—	3	1
Total snow courses	8	12	12	32